

Future scenarios of biological invasions threaten endemism in a neotropical basin

Cenários futuros de invasões biológicas ameaçam o endemismo em uma bacia neotropical

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ABSTRACT

Globalization and climate change are accelerating the introduction of non-native fish species, posing a threat to global biodiversity. However, monitoring of these species remains neglected in many Neotropical regions, and studies applying tools to detect and track invasions, especially at early stages, are still scarce. In the Iguaçu River Basin, southern Brazil, the uncontrolled introduction of non-native species has posed a risk to local endemism. Given the threat of negative impacts on regional biodiversity, this study aimed to assess the invasive potential and to model current and future (2040–2100) invasion scenarios for five non-native species in the Iguaçu River Basin. The Aquatic Species Invasiveness Screening Kit (AS-ISK) was used to determine the invasive potential of each of the five species analyzed, and ecological niche modeling was applied to evaluate the current and future environmental suitability of the target species. All five species assessed exhibited high potential invasion risk in the region. Current and future environmental suitability varied among species across sections of the basin and among the future periods analyzed; however, all of these species require early and urgent monitoring. In particular, *Cichla kelberi* and *Micropterus salmoides* (already recorded in the basin), as well as *Plagioscion squamosissimus* (not yet recorded), showed a high probability of near-term invasion, indicating the need for targeted management actions. Therefore, decision-makers should implement strict public policies to monitor and contain the spread of these species in the Iguaçu River Basin, ensuring the preservation of its endemic ichthyofaunal biodiversity and anticipating a potential environmental collapse and threats to the region's unique endemism.

Keywords: Non-native fish species; Iguaçu River Basin; AS-ISK; Niche modeling; Conservation

RESUMO

A globalização e as mudanças climáticas aceleram a introdução de espécies de peixes não nativas, representando uma ameaça à biodiversidade global. No entanto, o monitoramento dessas espécies permanece negligenciado em muitas regiões neotropicais, e estudos que empregam ferramentas para detectar e acompanhar invasões, especialmente em estágios iniciais, ainda são escassos. Na Bacia do Rio Iguaçu, no sul do Brasil, a introdução descontrolada de espécies não nativas tem representado um risco ao endemismo local. Diante da ameaça de impactos negativos à biodiversidade regional, este estudo teve como objetivo avaliar o potencial invasivo e modelar cenários atuais e futuros (2040–2100) de invasão de cinco espécies não nativas na Bacia do Rio Iguaçu. O *Aquatic Species Invasiveness Screening Kit* (AS-ISK) foi utilizado para determinar o potencial invasivo de cada uma das cinco espécies analisadas, e a modelagem de nicho ecológico foi aplicada para avaliar a adequabilidade ambiental atual e futura das espécies-alvo. As cinco espécies avaliadas apresentaram alto risco de invasão na região. A adequabilidade ambiental atual e futura variou entre as espécies, ao longo de diferentes trechos da bacia e entre os períodos futuros analisados, contudo, todas requerem monitoramento precoce e urgente, especialmente *Cichla kelberi* e *Micropterus salmoides* (registradas na bacia) e *Plagioscion squamosissimus* (não registrado), demonstrando alta probabilidade de invasão em breve, tornando necessárias ações de manejo direcionadas. Portanto, os tomadores de decisão devem implementar políticas públicas rigorosas para monitorar e conter a dispersão dessas espécies na Bacia do Rio Iguaçu e assegurar a preservação de sua biodiversidade ictiofaunística endêmica, antecipando um possível colapso ambiental e ameaça ao endemismo único do local.

Palavras-chave: Espécies de peixes não nativas; Bacia do Rio Iguaçu; AS-ISK; Modelagem de nicho; Conservação

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Introduction

The era of mass biodiversity extinction in the Anthropocene (Keck et al., 2025) has been driven primarily by the introduction of non-native species (Brito et al., 2020; Seebens et al., 2025), with freshwater ecosystems among the most affected (Keck et al., 2025). These introductions are mainly driven by aquaculture activities (Vitule et al., 2019; Garcia et al., 2022), sport fishing (Vitule, 2009; Vitule et al., 2014), inadequate planning and management, together with misguided and ecologically unsound social and political initiatives (Geller et al., 2020; Garcia et al., 2022; Pelicice et al., 2023). Although many species do not become invasive, others present a high invasion potential (Simberloff and Rejmánek, 2011). Given that climate change can generate a series of consequences for the distribution and ecology of invasive species, and those new invasions are predicted by 2050 (Seebens et al., 2021), it is necessary to use predictive methodologies for invasions by new organisms and their potential effects in a range of environments (Corrales et al., 2020), since prevention and early detection are effective and economical strategies to control invasions (Seebens et al., 2025).

In this context, occurrence lists and databases of potentially invasive species are valuable tools, providing accessible, up-to-date information to policymakers (Gilles Jr. et al., 2024). In addition, other tools can assist in identifying the invasion potential of non-native species. Among them, the screening protocol for assessing the invasion risk of freshwater fishes (*Aquatic Species Invasiveness Screening Kit* – AS-ISK) (Copp et al., 2016) and species distribution models, which relate occurrence records to environmental variables to estimate areas of suitability (Ruaro et al., 2019; Jan et al., 2024), are widely applied in invasion biology to predict risks and support management strategies (Barbet-Massin et al., 2018; Seebens et al., 2025).

However, in many regions, studies that apply tools to monitor biological invasions are still scarce, particularly in some Neotropical areas, which hold one-third of the global fish diversity and harbor the highest levels of species richness and endemism worldwide (Tonella et al., 2023), especially within two ecoregions in southern Brazil: Upper Paraná and Iguassu (Abell et al., 2008; Mezzaroba et al., 2021; Larentis et al., 2022; Dagosta et al., 2024). The Iguazu River Basin contains approximately 70% endemic fish species, of which 21% are threatened with extinction (Mezzaroba et al., 2021; Dagosta et al., 2024), and is recognized as a biodiversity hotspot: FEOW – Iguassu (Abell et al., 2008). Nonetheless, this ecoregion has come under increasing pressure due to the alarming introduction of non-native species (Vitule et al., 2014; Daga et al., 2016; Geller et al., 2025), which may jeopardize native biodiversity and associated ecosystem services.

The causes of translocation of non-native species among Brazilian hydrographic basins are diverse (Gubiani et al., 2018; Ruaro et al., 2019; Vitule et al., 2019), mainly involving species used for recreational fishing and those with economic value, such as black bass/largemouth bass (*Micropterus salmoides*) (Lacepède, 1802) (Pereira

and Vitule, 2019) and peacock bass (*Cichla* spp.) (Franco et al., 2022). In addition, other species are translocated due to their value as food fish or for restocking actions, such as silver croaker (*Plagioscion squamosissimus*) (Heckel, 1840) (Queiroz-Sousa et al., 2018), rainbow trout (*Oncorhynchus mykiss*) (Walbaum, 1792) (Latini et al., 2016), and species appreciated by aquarists, such as the Oscar (*Astronotus crassipinnis*) (Agassiz, 1831) (Magalhães et al., 2017). Given previous studies on negative effects in other regions of Brazil following the invasion of *M. salmoides* (Pereira and Vitule, 2019), *Cichla* spp. (Franco et al., 2022), *P. squamosissimus* (Queiroz-Sousa et al., 2018), *O. mykiss* (Spairani et al., 2025), and *A. crassipinnis* (Magalhães et al., 2017), and the low abundance or even absence of these species in the Iguazu River Basin, we consider it essential to investigate their establishment potential.

Thus, some non-native species already recorded in the Iguazu River Basin, southern Brazil, as well as new potentially invasive species, may expand in the region due to climate change and anthropogenic alterations to ecosystems. We therefore defined the objectives as follows: to assess the invasion potential of five non-native species three with sporadic records and two never recorded in the Iguazu River Basin and to model their invasion under different future climate scenarios.

Methods

Study area

Most of the Iguazu River Basin is located in the southern portion of the State of Paraná, Brazil, covering 54,820 km², with portions in Santa Catarina, Brazil (13,470 km²), and Misiones, Argentina (1,837.5 km²), for a total of 70,127.5 km² (Baumgartner et al., 2012). The formation of the basin dates back to the Mesozoic era through the early Paleozoic and is associated with stepped uplift movements of the Serra do Mar (Mineropar, 2010), which gave rise to the three Paraná plateaus: (1) Curitiba region, (2) Ponta Grossa region, and (3) Guarapuava region (Maack, 2001). These three plateaus divide the basin into three regions (Figure 1): Upper Iguazu (first plateau), Middle Iguazu (second), and Lower Iguazu (third plateau) (Maack, 2001; Baumgartner et al., 2012).

Selection of species

For the survey of non-native species in the Iguazu River Basin, we consulted the most recently compiled species list for the basin, prepared by Mezzaroba et al. (2021). Subsequently, scientific databases (SciELO, Google Scholar, and PubMed) were searched using a temporal filter from 2010 to 2025, applying the keywords “Iguazu,” “Iguassu,” “Iguazu Basin,” and “Iguassu Basin” to identify possible new records of non-native species in the region. Based on the non-native fish species listed for the Iguazu River Basin, five species were selected for assessment of invasion potential: three with sporadic

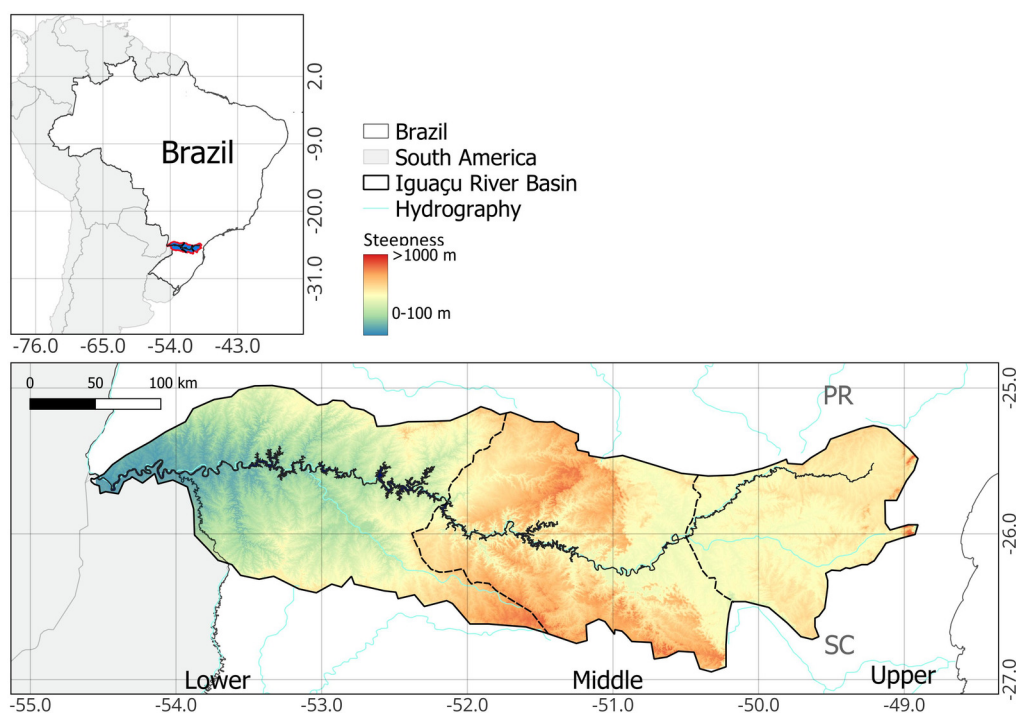


Figure 1 – Location and geomorphological division (upper, middle, and lower) of the Iguazu River Basin.

records in the region: *M. salmoides* (largemouth bass), *C. kelberi* (peacock bass), and *O. mykiss* (rainbow trout) and two without confirmed previous records: *P. squamosissimus* (silver croaker) and *A. crassipinnis* (Oscar). The selection was based on the well-documented history of invasive biological behavior of these species in the literature, as well as alerts issued by the International Union for Conservation of Nature (IUCN, 2026), which lists them among the most frequently introduced species in Brazil and worldwide (Dueñas et al., 2021). Other ecological and behavioral characteristics were also considered in the selection, such as voracious predatory habits, high dietary plasticity, large adult body size (>40 cm total length, TL), records of invasion in more than three Neotropical basins, evidence of establishment and habitat degradation in other regions of Brazil, and confirmed presence or geographic proximity to the Iguazu River Basin (Magalhães et al., 2017; Queiroz-Sousa et al., 2018; Pereira and Vitule, 2019; Franco et al., 2022; Spairani et al., 2025).

Aquatic Species Invasiveness Screening Kit (AS-ISK)

The tool used to identify potentially invasive species was the *Aquatic Species Invasiveness Screening Kit* (AS-ISK), which is available for download at www.cefas.co.uk/nns/tools/. The procedures associated with the tool are described in Copp et al. (2016). AS-ISK consists of 49 questions (Qs) grouped into two main sections: the biogeographical and historical characteristics of the taxon (13 Qs in total) and its biological and ecological interactions (36 Qs in total), thereby providing the Basic Risk Assessment (BRA). This assessment

is complemented by six additional Climate Change Assessment (CCA) questions that predict how future climatic conditions may affect the AS-ISK evaluation, bringing the total to 55 questions. The confidence-ranking categories are: 1 = low, 2 = medium, 3 = high, 4 = very high. In all cases, an overall score < 1 assigns the status of “low risk” (i.e., not likely to be invasive), whereas values ≥ 1 indicate alien species as potentially invasive, representing either “medium risk” or “high risk” (Copp et al., 2016). It is advisable to identify a “threshold” value for the risk assessment area (RA) through a “calibration” process to distinguish between medium- and high-risk invasive species (Copp, 2013; Copp et al., 2016). Possible scores range from –20 to 68 for BRA, and from –32 to 80 for BRA+CCA. Graphical analyses were performed in R (R Core Team, 2024) and radar charts were produced using the packages *fmsb*, *ggplot2*, and *scales*.

Occurrence data

Occurrence records for the five target species were obtained from online databases of zoological collections, including the Centro de Referência em Informação Ambiental (SpeciesLink) and the Global Biodiversity Information Facility (GBIF), considering data published up to May 2025. After collection, georeferenced records with decimal-degree latitude and longitude coordinates were organized into .csv tables for each species: *M. salmoides* (16,884 occurrences), *C. kelberi* (294), *O. mykiss* (3,375), *P. squamosissimus* (1,693), and *A. crassipinnis* (1,061). To ensure data consistency, records with invalid coordinates or missing values were discarded, thereby minimizing

geolocation errors that could negatively affect the accuracy of the distribution models (Supplementary Material 1).

Furthermore, to reduce the effect of multiple records from heavily sampled locations and spatial autocorrelation, the data were partitioned into spatial blocks using the `blockCV` function from the `ENMeval` package (Kass et al., 2021). This approach enables a more robust evaluation of model performance by ensuring that training and testing datasets are spatially independent.

Environmental data

The environmental variables used as abiotic predictors were obtained using the `worldclim_global` function from the `geodata` package (Hijmans et al., 2024) in R (R Core Team, 2024). These corresponded to the 19 bioclimatic variables (BIO1–BIO19) from the WorldClim version 2.1 dataset (Fick and Hijmans, 2017). The raster layers were downloaded at a spatial resolution of 2.5 arc-minutes (~5 km) and subsequently cropped to encompass the Americas (South, Central, and North America, as well as the Caribbean), where most occurrence records were concentrated. To reduce multicollinearity among environmental predictors, a Variance Inflation Factor (VIF) analysis was applied using the `vifstep` function from the `usdm` package (Naimi et al., 2014) in R (R Core Team, 2024). A VIF threshold of > 3 was adopted, following recommended practices in ecological niche modeling (Araújo et al., 2019).

Spatial delimitation and background generation

For each occurrence dataset, environmental values associated with each point were extracted, and records with missing data (NA) were discarded. A 500 km buffer was then constructed around all occurrence points. Within this delimited area, 10,000 random background points were generated using the `spatSample` function from the `terra` package (Hijmans, 2025), implemented in R (R Core Team, 2024). These points were used as negative contrasts in the modeling process, being treated as absences by the Maxent algorithm.

Niche modeling

Potential distribution models were built using the `ENMevaluate` function from the `ENMeval` package (Kass et al., 2021), employing the maxnet algorithm (Phillips et al., 2017), a reimplementation of Maxent (Phillips et al., 2006) in R (R Core Team, 2024) with enhanced flexibility and performance. For each species, different combinations of model complexity were tested by varying the following components: (i) Feature classes (fc): These determine how environmental variables are transformed before being used in the models, directly influencing the shape of environmental responses. The tested feature classes were: (a) Linear (L), which assumes a linear relationship between predictor variables and species presence; (b) Quadratic (Q), which adds squared terms (x^2), allowing unimodal responses (e.g., species presence peaking at intermediate environmental values);

(c) Hinge (H), which allows abrupt changes in the slope of the response; and (d) LQ and LQH, combinations of the above, which enable more complex and flexible responses to environmental gradients. (ii) Regularization multiplier (rm): This parameter penalizes model complexity. Higher rm values yield simpler, more generalist models, whereas lower values allow tighter fits to the training data. Values of rm from 1 to 5 (in increments of 1) were tested. Each model combination (defined by the chosen fc and rm values) was evaluated based on three primary performance metrics: (i) AICc (Corrected Akaike Information Criterion) – used to compare model quality by balancing model fit and complexity, penalizing overparameterization. Lower values indicate more parsimonious models with better trade-offs between fit and simplicity; (ii) CBI (Continuous Boyce Index), used to assess the model's ability to distinguish areas with higher versus lower suitability. Values near 1 indicate strong performance, whereas values near 0 suggest random prediction; (iii) 10th Percentile Omission Rate – represents the proportion of occurrence records with suitability values below the threshold retaining 90% of training data. Lower omission rates indicate higher predictive capacity with fewer false negatives. Model selection was based on a complementary assessment of these three metrics, prioritizing models with low AICc, high CBI, and low omission rates. After calibration, the best-performing models were projected onto three future climatic periods (2040–2060, 2060–2080 and 2080–2100), considering only the most pessimistic emission scenario (SSP5-8.5). The niche modeling maps were produced in R (R Core Team, 2024).

Results

Potential intruder AS-ISK protocol

The classification of fish species in the Iguaçu River Basin (RA) was based on the proposed calibration. Scores below 0 indicate low invasion risk; scores between 0 and 24 indicate medium invasion risk; and scores above 24 indicate high invasion risk. All five species evaluated exhibited a high invasion risk (score > 24) in the RA. The species with the highest BRA score was *C. kelberi*, followed by *M. salmoides* (both already recorded in the basin) and *P. squamosissimus* (not yet recorded). *Astronotus crassipinnis* and *O. mykiss* showed the lowest scores, close to the threshold for medium risk. In the composite score results (BRA+CCA), there was a slight change, with *C. kelberi* followed by *P. squamosissimus* and *M. salmoides* (Table 1, Figure 2).

In the detailed assessment of the AS-ISK protocol, *C. kelberi*, *M. salmoides*, and *P. squamosissimus* showed the highest values in the Biogeography/History criterion, indicating a broad geographical distribution or a more established introduction history across different regions, with the first two species already recorded in the RA. In contrast, *A. crassipinnis* and *O. mykiss* exhibited lower scores in this criterion, suggesting more recent introductions or a more restricted historical distribution. In the specific case of *A. crassipinnis*, the absence

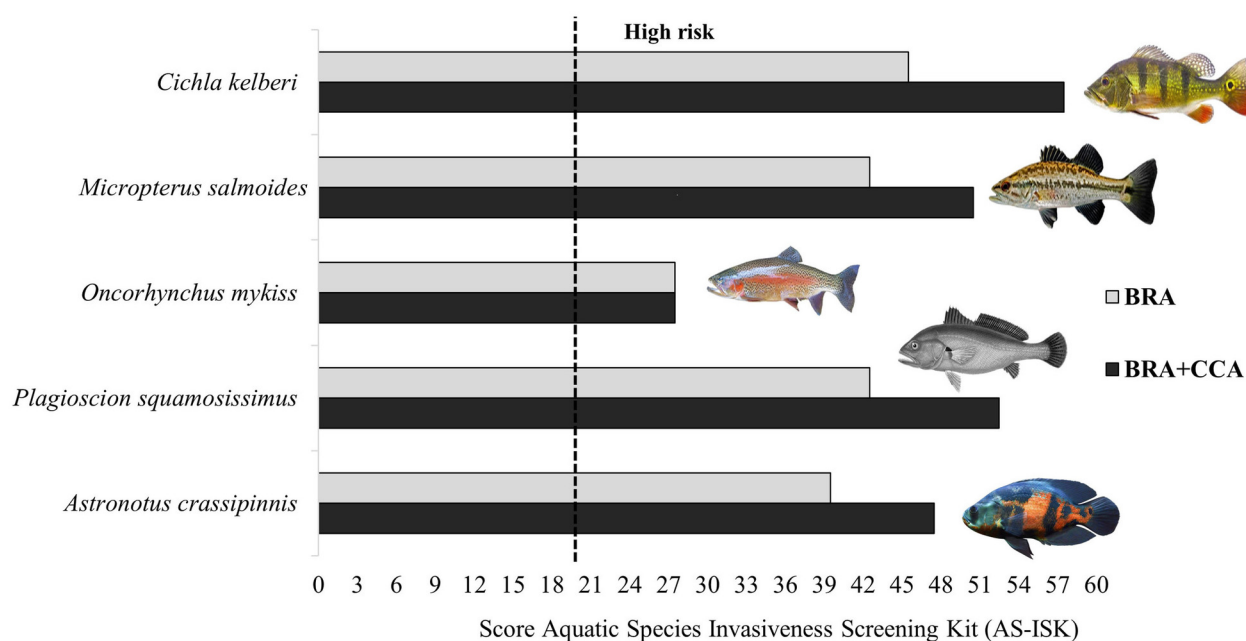


Figure 2 – Final scores of the five non-native fish species evaluated with the AS-ISK protocol for the Iguaçu River Basin with the high-risk score. Basic score (BRA). Composite score with Climate Change (BRA+CCA).

Table 1 – Final AS-ISK scores regarding invasion risk for the five target species in the Iguaçu River Basin (RA). BRA = Basic Risk; BRA+CCA = Composite score including Climate Change Assessment.

Species	Score			Reliability			
	BRA	BRA+CCA	Risk	BRA	CCA	BRA+CCA	Risk
<i>Cichla kelberi</i>	45.50	57.50	High	0.65	0.46	0.63	High
<i>Micropterus salmoides</i>	42.50	50.50	High	0.75	0.46	0.72	High
<i>Plagioscion squamosissimus</i>	42.50	52.50	High	0.73	0.50	0.71	High
<i>Astronotus crassipinnis</i>	39.50	47.50	High	0.76	0.50	0.65	High
<i>Oncorhynchus mykiss</i>	27.50	27.50	High	0.69	0.25	0.65	High

of records in the RA may have contributed to the reduced score (Figure 3 and Supplementary Material 2).

Ecological niche modeling (ENM)

The models for *C. kelberi* showed acceptable predictive performance across all three temporal scenarios. Under current conditions, the optimal model combined LQH features with a regularization multiplier (rm) of 1; this configuration remained the most parsimonious for both the 2040–2060 and 2080–2100 periods. Models developed for *M. salmoides* exhibited good predictive performance across all temporal scenarios (current, 2040–2060 and 2080–2100). Similarly, models for *O. mykiss* demonstrated excellent predictive performance across all evaluated periods. For *P. squamosissimus*, model performance was acceptable in all three temporal scenarios, whereas models for *A. crassipinnis* showed reasonable predictive performance throughout the analyzed periods (Supplementary Material 3).

The projected suitability maps for the target species indicate variations in invasive potential across different stretches of the Iguaçu River Basin (Upper, Middle, and Lower) under current and future scenarios. For the three species already recorded in the basin, the present scenario shows broad habitat suitability. However, future projections indicate a reduction in potential distribution, particularly for *O. mykiss*, while *C. kelberi* is expected to maintain high suitability in the medium term (2040–2060). *M. salmoides* shows consistently high suitability across all periods, with an intensification predicted for 2060–2100. The models also suggest that environmental suitability may increase over time for the two species not yet recorded in the Iguaçu River Basin. *Plagioscion squamosissimus* currently exhibits high suitability in the Lower Iguaçu region, maintaining this pattern in the intermediate scenario (2040–2060) but showing a decrease in long-term projections (2060–2100). *Astronotus crassipinnis* displays moderate suitability in the Upper Iguaçu region across all evaluated scenarios (Figure 4).

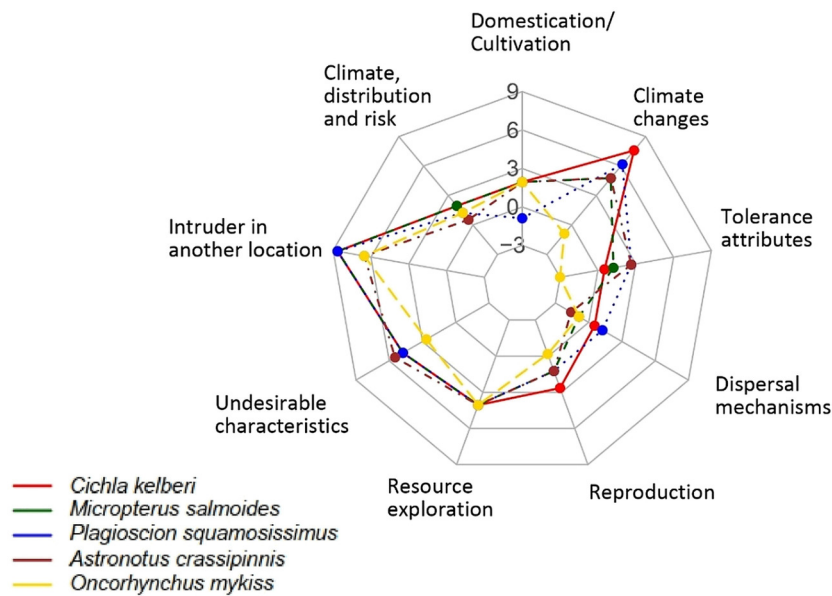


Figure 3 – Detailed AS-ISK scoring results divided by attribute blocks for the five non-native species evaluated in the Iguazu River Basin (RA).

Discussion

By integrating invasion risk screening (AS-ISK) with ecological niche modeling, our study identifies species-specific invasion trajectories and spatially explicit risk patterns under climate change in one of the most endemic Neotropical River basins. South American policies reflect the low level of public interest in aquatic invasive species (AIS). At the national level, policies in South America are poorly developed and largely focused on alien species that threaten productive and political systems. Both low-cost, high-reliability methodologies applied here demonstrate an imminent risk to the Iguazu River Basin that cannot be ignored by Brazilian federal and state public policies, particularly regarding the target species. The values obtained for the basic score (BRA) and the composite score (BRA+CCA), combined with ecological niche modeling (2040–2100), indicate that management and prevention actions should initially be directed toward two species: *Cichla kelberi* (yellow peacock bass) and *Micropterus salmoides* (largemouth bass). These two species exhibit biological characteristics favorable to invasion, such as ecological plasticity, high reproductive rates, and predatory behavior, and are also associated with anthropogenic risk factors. Both species have already been recorded in the Iguazu River Basin: *C. kelberi* in the lower Iguazu region and *M. salmoides* throughout the basin.

Peacock bass species of the genus *Cichla* are widely introduced in freshwater systems (Agostinho et al., 2004; Marques et al., 2016; Franco et al., 2022) and cause serious ecological effects (Pelicice et al., 2015; Franco et al., 2021). These piscivorous species exhibits voracious behavior and remarkable phenotypic, behavioral, and hunting plasticity (Gaspar et al., 2025). Based on these traits, it is evident that an invasion of *C. kelberi* in the Iguazu River could harm the native

ichthyofauna, especially small-bodied species whose decline following invasions is well documented (Franco et al., 2021; Rauber et al., 2024; Gaspar et al., 2025). The species' ability to adapt to modified environments (Catelani et al., 2021; Franco et al., 2022) reinforces the importance of monitoring it in the basin. Although previous studies have shown that their establishment and dispersal have been limited by the low mean water temperature (below 20 °C) in the Iguazu River Basin, our scenarios, together with projections of increasing global mean temperatures (Intergovernmental Panel on Climate Change (IPCC) in 2007), reveal a shift in this pattern, allowing non-native species that were previously constrained by water temperature to become established. Supporting our projections, Franco et al. (2022) identified critical points for *Cichla* invasion concentrated in tropical climatic zones, especially in the Upper Paraná ecoregion.

Micropterus salmoides (largemouth bass) occurs on all continents except Antarctica and has been included since 2004 on the IUCN list of the "100 worst invasive alien species" (Lowe et al., 2000). Multiple negative effects of its invasion are well documented (see Pereira and Vitule, 2019; Costantini et al., 2023; Culbertson et al., 2024), supported by specific adaptations such as tolerance to low oxygen levels and wide water temperature ranges, generalist feeding behavior, trophic plasticity, and the ability to occupy multiple ecological niches (Mulhollem et al., 2016; Peat et al., 2016; Costantini et al., 2023). Although the AS-ISK protocol did not identify *M. salmoides* as having the highest basic invasive potential (BRA), current and future modeling projections highlight this species as a potential concern. As with peacock bass, successful invasions of largemouth bass occur predominantly in disturbed habitats (reservoirs), whereas their presence in rivers and streams is considerably lower (Pereira and Vitule, 2019;

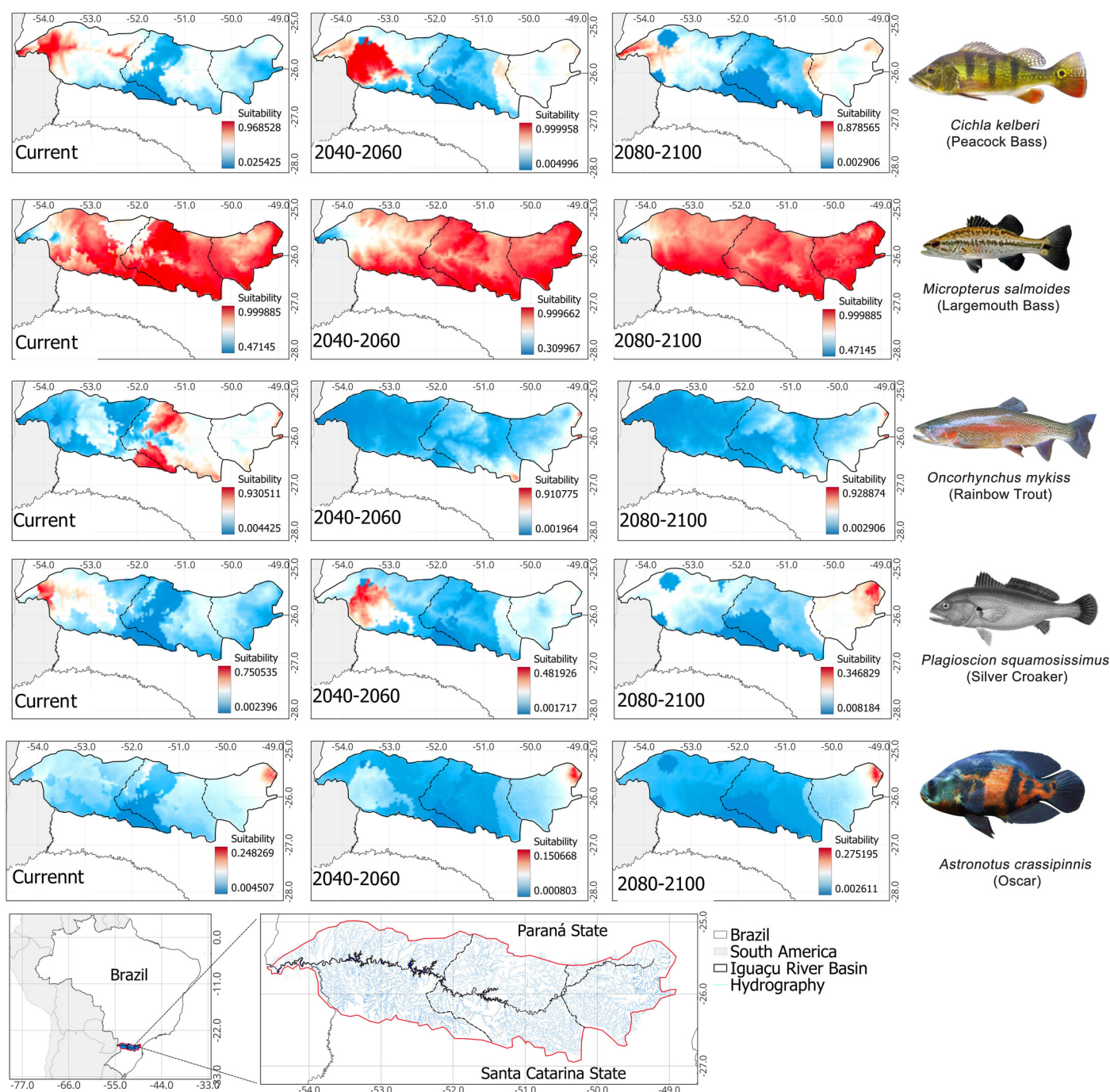


Figure 4 – Ecological niche models (ENM) for the five target non-native fish species in the Iguazu River Basin under current conditions (2025) and future scenarios (2040–2060 and 2060–2100).

Freitas et al., 2023). Although projections indicate high environmental suitability for this species in the future (Figure 3), the reservoir characteristics of the Iguazu River, along with numerous tributaries with cold, flowing waters, create less favorable conditions for its proliferation in tributaries. However, this scenario signals a warning for the future: the expansion of hydropower facilities and resulting alter-

ation of natural habitats, combined with future climate change, may create conditions more conducive to invasion, especially in the main channel of the Iguazu River. This pattern is corroborated by Freitas et al. (2023), who recorded *M. salmoides* in the Passaúna Reservoir near the state capital.

Ranked as the third species in the AS-ISK basic score and second in the composite score, and also presenting suitable areas in the modeling projections, as additionally revealed by other distributional projections (Ferreira et al., 2025), the silver (*Plagioscion squamosissimus*) was initially introduced in northeastern and southeastern Brazil and is currently one of the main introduced species in the country (Queiroz-Sousa et al., 2018; Orlandi-Neto et al., 2024). Considering the high scores obtained in the protocol and the niche modeling projections, the species can be categorized as a potential invader of the Iguaçu River Basin, especially in the lower Iguaçu, an area highly modified by cascade reservoirs. Numerous negative effects have already been documented in invaded areas such as the Jaguari Reservoir (Orlandi-Neto et al., 2024), the Doce River (Barros et al., 2012), and other regions of Brazil (Queiroz-Sousa et al., 2018). This taxon is a generalist carnivore that exhibits ontogenetic dietary shifts (Neves et al., 2015).

Relevant results, although less critical, were observed for *Oncorhynchus mykiss* (rainbow trout). The species showed the lowest invasive potential in the AS-ISK, at both the basic and composite levels, compared with the other species. However, it still presented a high invasion risk in the Iguaçu River Basin according to RA calibration. Nevertheless, in projections for later periods (2060–2100), a decrease in suitability was observed, most likely due to global temperature increases, a pattern already reported for the species by Yogurtçuoğlu et al. (2021), who found a reduction in the invasion potential of *O. mykiss* in Turkey due to rising temperatures. Genetic studies in trout populations have been conducted to increase resistance to temperature changes (Araújo et al., 2023), which could make this species more resilient to warming and a concern in cases of escapes from aquaculture. Thus, the species cannot be fully disregarded, as it exhibits carnivorous habits, preying on various invertebrates and small fish, in addition to being a highly adaptable and competitive generalist (Yogurtçuoğlu et al., 2021; Sunny et al., 2024; Spairani et al., 2025). Therefore, careful monitoring of this species is necessary, especially in the coming years, considering that it is not yet widely established in the basin.

Astronotus crassipinnis (Oscar), native to the Amazon Basin in Peru, Colombia, and Brazil, is now distributed across several regions of Brazil (Magalhães et al., 2019; Pavanelli et al., 2023) and beyond South America (Lozano et al., 2022). The species showed intermediate results in the AS-ISK protocol and low suitability in the niche models for the entire Iguaçu River Basin, with isolated areas of potential invasion, mainly in the coastal region of the upper Iguaçu. Under climate change scenarios, rising average water temperatures may lead to the redistribution of fish species such as *A. crassipinnis*, as warmer waters facilitate the spread of non-native tropical fish to higher latitudes (Sharma et al., 2007; Rahel and Olden, 2008). This species is widely used in the aquarium trade and exhibits aggressive biological behavior. Propagule pressure is generally high, which is a concerning

factor not captured by future niche modeling. The risk of invasion driven by propagule pressure from *A. crassipinnis* is constant across Brazil, largely due to irresponsible aquarium releases (Magalhães et al., 2017; Ferraz et al., 2019).

Although carnivorous fish are considered among the most successful invasive species, taxa from lower trophic levels with generalist feeding habits may also benefit from biological invasions due to their dietary plasticity (Agostinho et al., 2015; Tonella et al., 2018). The species analyzed in this study are carnivorous and generalists, many exhibiting notable trophic plasticity, especially in novel environments, reinforcing the hypothesis of a possible invasion sequence in the Iguaçu River Basin. Notably, most of the non-native species evaluated, especially *C. kelberi*, *M. salmoides*, and *P. squamosissimus*, tend to benefit from lentic environments, which are often associated with human activities. The upper Iguaçu shows high pollution levels, mainly due to industrial and domestic effluent discharge (Bueno-Krawczyk et al., 2015), a pattern also observed in the middle Iguaçu (Krawczyk et al., 2023), along with the presence of pesticides used in agricultural practices in the middle and lower regions of the basin (Nimet et al., 2017).

The integration of AS-ISK and ENMs provides complementary, though non-equivalent, perspectives on invasion risk. While AS-ISK captures species-level traits, invasion history, and potential impacts, ENMs characterize the spatial and climatic constraints shaping species establishment and spread. The convergence of high AS-ISK scores and broad environmental suitability for *Cichla kelberi* and *Micropterus salmoides* strengthens confidence in their invasion potential in the Iguaçu River Basin. Conversely, species classified as high risk by AS-ISK but exhibiting spatially restricted environmental suitability highlight the role of environmental filtering in shaping invasion outcomes under future climate scenarios. Nevertheless, this pilot study for the Iguaçu River Basin serves as an initial warning to Brazilian federal and state political and environmental authorities to initiate monitoring and control programs for non-native species in this highly endemic region, which faces a substantial risk of biodiversity loss.

Conclusion

The combination of ecological niche modeling and data obtained through the AS-ISK protocol reveals an imminent threat of biological invasions in the Iguaçu River basin, especially under a scenario of climate change. These results reinforce the urgency of prevention and management strategies for all species evaluated, especially for *Cichla kelberi* and *Micropterus salmoides*, which have already been recorded in the basin, as well as *Plagioscion squamosissimus*, which has not yet been recorded.

Despite recurrent warnings about the impacts of biological invasions in aquatic environments, awareness of the problem's severity remains low, and effective actions are scarce. Therefore, this study reinforces the need for more rigorous public policies, grounded in

scientific evidence, to curb the spread of non-native species in the Iguaçu River Basin.

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References

- Abell, R.; Thieme, M.L.; Revenga, C.; Bryer, M.; Kottelat, M. et al., 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. *BioScience*, v. 58 (5), 403-414. <https://doi.org/10.1641/B580507>.
- Agostinho, A.A.; Gomes, L.C.; Latini, J.D., 2004. Fisheries management in Brazilian reservoirs: lessons from and for South America. *Interciencia*, v. 29 (6), 1-9.
- Agostinho, A.A.; Suzuki, H.I.; Fugi, R.; Alves, D.C.; Tonella, L.H. et al., 2015. Ecological and life history traits of *Hemiodus orthonops* in the invasion process: looking for clues at home. *Hydrobiologia*, v. 746, 415-430. <https://doi.org/10.1007/s10750-014-2030-2>
- Araújo, M.B.; Anderson, R.P.; Barbosa, A.M.; Beale, C.M.; Dormann, C.F. et al., 2019. Standards for distribution models in biodiversity assessments. *Science Advances*, v. 5, eaat4858. <https://doi.org/10.1126/sciadv.aat4858>.
- Araújo Júnior, N.T.; Ianella, P.; Yoshinaga, T.T.; Butzge, A.J.; Caetano, A.R., 2023. Population structure and genetic diversity of rainbow trout (*Oncorhynchus mykiss*) broodstocks from Brazil using SNP markers. *Aquaculture Reports*, v. 31, 101689. <https://doi.org/10.1016/j.aqrep.2023.101689>.
- Barbet-Massin, M.; Rome, Q.; Villemant, C.; Courchamp, F., 2018. Can species distribution models really predict the expansion of invasive species? *PLoS ONE*, v. 13 (3), e0193085. <https://doi.org/10.1371/journal.pone.0193085>.
- Barros, L.C.; Santos, U.; Zanuncio, J.C.; Dergam, J.A., 2012. *Plagioscion squamosissimus* and *Parachromis managuensis*: a threat to native fishes of the Doce River, Brazil. *PLoS ONE*, v. 7, e39138. <https://doi.org/10.1371/journal.pone.0039138>
- Baumgartner, G.; Pavanelli, C.S.; Baumgartner, D.; Bifi, A.G.; Debona, T. et al., 2012. Peixes do baixo rio Iguaçu. EDUEM, Maringá.
- Brito, M.F.G.; Daga, V.S.; Vitule, J.R.S., 2020. Fisheries and biotic homogenization of freshwater fish in the Brazilian semiarid region. *Hydrobiologia*, v. 847, 3877-3895. <https://doi.org/10.1007/s10750-020-04236-8>
- Bueno-Krawczyk, A.C.D.; Guiloski, I.C.; Piancini, L.D.S.; Azevedo, J.C.; Ramsdorf, W.A. et al., 2015. Multibiomarker in fish to evaluate a river used for public water supply. *Chemosphere*, v. 135, 247-264.
- Catelani, P.A.; Petry, A.C.; Pelicice, F.M.; García-Berthou, E., 2021. When a freshwater invader meets the estuary: the peacock bass and fish assemblages in the São João River, Brazil. *Biological Invasions*, v. 23, 167-179. <https://doi.org/10.1007/s10530-020-02363-w>
- Copp, G.H., 2013. The Fish Invasiveness Screening Kit (FISK) for non-native freshwater fishes: a summary of current applications. *Risk Analysis*, v. 33, 1394-1396. <https://doi.org/10.1111/risa.12095>.
- Copp, G.H.; Vilizzi, L.; Tidbury, H.; Stebbing, P.D.; Tarkan, A.S. et al., 2016. Development of a generic decision-support tool for identifying potentially invasive aquatic taxa: AS-ISK. *Management of Biological Invasions*, v. 7 (4), 343-350. <https://doi.org/10.3391/mbi.2016.7.4.04>.
- Corrales, X.; Katsanevakis, S.; Coll, M.; Heymans, J.J.; Piroddi, C. et al., 2020. Advances and challenges in modelling the impacts of invasive alien species on aquatic ecosystems. *Biological Invasions*, v. 22 (3), 907-934. <https://doi.org/10.1007/s10530-019-02160-0>
- Costantini, M.L.; Kabala, J.P.; Sporta Caputi, S.; Ventura, M.; Calizza, E. et al., 2023. Biological invasions in fresh waters: *Micropterus salmoides*, an American fish conquering the world. *Water*, v. 15, 3796. <https://doi.org/10.3390/w15213796>.
- Culbertson, A.E.; Nakamoto, B.; Lento, J.; Curry, R.A.; Harrison, P.M., 2024. New bass on the block: trophic interactions among invasive largemouth bass *Micropterus salmoides* and local sportfish. *Journal of Fish Biology*, v. 106 (3), 784-796. <https://doi.org/10.1111/jfb.15997>
- Daga, V.S.; Debona, T.; Abilhoa, V.; Gubiani, É.A.; Vitule, J.R.S., 2016. Non-native fish invasions of a Neotropical ecoregion with high endemism: a review of the Iguaçu River. *Aquatic Invasions*, v. 11 (2), 209-223. <https://doi.org/10.3391/ai.2016.11.2.10>.
- Dagosta, F.C.P.; Monção, M.S.; Nagamatsu, B.A.; Pavanelli, C.S.; Carvalho, F.R. et al., 2024. Fishes of the upper rio Paraná basin: diversity, biogeography

- and conservation. *Neotropical Ichthyology*, v. 22 (1), e230066. <https://doi.org/10.1590/1982-0224-2023-0066>.
- Dueñas, M.A.; Hemming, D.J.; Roberts, A.; Diaz-Soltero, H., 2021. The threat of invasive species to IUCN-listed critically endangered species: a systematic review. *Global Ecology and Conservation*, v. 26, e01476. <https://doi.org/10.1016/j.gecco.2021.e01476>.
- Ferraz, J.D.; Casimiro, A.C.R.; Pereira, A.D.; Garcia, D.A.Z.; Jarduli, L.R. et al., 2019. Aquarismo “jumbo”: representa um potencial para introdução de espécies no Brasil? *Oecologia Australis*, v. 23 (3), 519-535. <https://doi.org/10.4257/oeco.2019.2303.11>.
- Ferreira, V.G.; Conceição, E.O.; Mantovano, T.; Melo, R.G.; Rosa, J. et al., 2025. Distributional projections of an Amazonian fish in native and non-native watersheds of South America in response to climate change. *Biological Invasions*, v. 27, 201. <https://doi.org/10.1007/s10530-025-03655-9>
- Fick, S.E.; Hijmans, R.J., 2017. WorldClim 2: new 1 km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, v. 37 (12), 4302-4315. <https://doi.org/10.1002/joc.5086>.
- Franco, A.C.S.; García-Berthou, E.; Santos, L.N., 2021. Ecological impacts of an invasive top predator fish across South America. *Science of the Total Environment*, v. 761, 143296. <https://doi.org/10.1016/j.scitotenv.2020.143296>.
- Franco, A.C.S.; Petry, A.C.; Tavares, M.R.; Guimarães, T.F.R.; Santos, L.N., 2022. Global distribution of the South American peacock basses (*Cichla* spp.) follows human interference. *Fish and Fisheries*, v. 23 (2), 407-421. <https://doi.org/10.1111/faf.12624>.
- Freitas, M.O.; Ribeiro, V.M.; Abilhoa, V.; Vitule, J.R.S., 2023. Reproduction of the invasive largemouth bass *Micropterus salmoides* in a Neotropical reservoir with suggestions to management and control. *Acta Limnologica Brasiliensia*, v. 35, e11. <https://doi.org/10.1590/S2179-975X6822>.
- Garcia, D.A.; Occhi, T.V.; Agostinho, Á.A.; Alves, G.H.; Brito, M.F. et al., 2022. More of the same: new policies continue fostering the use of non-native fish in Brazil. *Environmental Conservation*, v. 49 (1), 4-7. <https://doi.org/10.1017/S0376892922000029>.
- Gaspar, M.R.; Agostinho, A.A.; Catelani, P.A.; Fernandes, R.; Franco, A.C.S. et al., 2025. Phenotypic and behavioral variation as a mechanism behind the invasive potential of a predatory neotropical fish. *Hydrobiologia*, v. 852, 2133-2147. <https://doi.org/10.1007/s10750-024-05663-7>.
- Geller, I.V.; Garcia, D.A.Z.; Casimiro, A.C.R.; Pereira, A.D.; Jarduli, L.R. et al., 2020. Good intentions, but bad effects: environmental laws protect non-native ichthyofauna in Brazil. *Fisheries Management and Ecology*, v. 28 (1), 14-17. <https://doi.org/10.1111/fme.12446>.
- Geller, I.V.; Vitule, J.R.S.; Ferraz, J.D.; Pereira, A.D.; Orsi, M.L., 2025. Current and future invasion of a predator with potential for negative impacts in a region of high Neotropical endemism. *Neotropical Ichthyology*, v. 23 (2), e250056. <https://doi.org/10.1590/1982-0224-2025-0056>.
- Gilles Jr., A.S.; Bate, J.M.B.; Solomon, M.A.K.; Peralta, E.M.; Pavia Jr, R.T.B. et al., 2024. Quantifying the current and future risk of invasiveness of non-native fishes in Ramsar-listed Lake Naujan, Philippines. *The Philippine Journal of Fisheries*, v. 31 (2). <https://doi.org/10.31398/tjpf/31.2.2023-0083>
- Gubiani, É.A.; Ruaro, R.; Ribeiro, V.R.; Eichelberger, A.C.A.; Bogoni, R.F. et al., 2018. Non-native fish species in Neotropical freshwaters: how did they arrive, and where did they come from? *Hydrobiologia*, v. 817 (1), 57-69. <https://doi.org/10.1007/s10750-018-3617-9>.
- Hijmans, R.J.; Barbosa, M.; Ghosh, A.; Mandel, A., 2024. geodata: Download geographic data. R package, version 0.6-2. <https://CRAN.R-project.org/package=geodata>.
- Hijmans, R., 2025. terra: Spatial data analysis. R package, version 1.8-29. <https://CRAN.R-project.org/package=terra>.
- Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, 104 p. <https://www.ipcc.ch/report/ar4/syr/>.
- International Union for Conservation of Nature (IUCN), 2026. The IUCN Red List of Threatened Species. Version 2026-1. <https://www.iucnredlist.org>.
- Jan, A.; Giannico, G.; Arismendi, I.; Flitcroft, R., 2024. Unveiling climatic niches for deeper insights into invasion potential and enhanced distribution models of freshwater fishes. *Ecology of Freshwater Fish*, v. 33 (4), e12784. <https://doi.org/10.1111/eff.12784>.
- Kass, J.M.; Muscarella, R.; Galante, P.J.; Bohl, C.L.; Pinilla-Buitrago, G.E. et al., 2021. ENMeval 2.0: redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods in Ecology and Evolution*, v. 12 (9), 1602-1608. <https://doi.org/10.1111/2041-210X.13628>.
- Keck, F.; Peller, T.; Alther, R.; Barouillet, C.; Blackman, R. et al., 2025. The global human impact on biodiversity. *Nature*, v. 641, 395-400. <https://doi.org/10.1038/s41586-025-08752-2>.
- Krawczyk, A.C.D.D.B.; Silva, M.D.M.; Rosa, J.; Gemelli, E.; Ribeiro, M.O. et al., 2023. Meio ambiente: alterações antrópicas no leito de rios e efluentes urbanos promovendo efeitos ecotoxicológicos na ictiofauna e na saúde pública: um estudo de caso. *Saúde e Meio Ambiente - Revista Interdisciplinar*, v. 12, 279-291.
- Larentis, C.; Kotz Kliemann, B.C.; Neves, M.P.; Delariva, R.L., 2022. Effects of human disturbance on habitat and fish diversity in Neotropical streams. *PLoS One*, v. 17 (9), e0274191. <https://doi.org/10.1371/journal.pone.0274191>
- Latini, A.O.; Oporto, L.T.; Lima-Júnior, D.P.; Resende, D.C.; Latini, R.O., 2016. Peixes. In: Latini, A.O.; Resende, D.C. (Eds.), *Espécies exóticas invasoras de águas continentais no Brasil*. Ministério do Meio Ambiente, Brasília, pp. 295-581.
- Lowe, S.; Browne, M.; Boudjelas, S.; De Poorter, M., 2000. 100 of the world's worst invasive alien species: a selection from the global invasive species database. *Global Invasive Species Programme*, Auckland.
- Lozano, A.P.; Lasso-Alcalá, O.M.; Bittencourt, P.S.; Taphorn, D.C.; Perez, N. et al., 2022. A new species of *Astronotus* (Teleostei, Cichlidae) from the Orinoco River and Gulf of Paria basins, northern South America. *ZooKeys*, v. 1113, 111-152. <https://doi.org/10.3897/zookeys.1113.81240>
- Maack, R., 2001. Breves notícias sobre a geologia dos estados do Paraná e Santa Catarina. *Brazilian Archives of Biology and Technology*, 169-288.
- Magalhães, A.L.; Orsi, M.L.; Pelicice, F.M.; Azevedo-Santos, V.M.; Vitule, J.R.S. et al., 2017. Small size today, aquarium dumping tomorrow: sales of juvenile non-native large fish as an important threat in Brazil. *Neotropical Ichthyology*, v. 15 (4), e170033. <https://doi.org/10.1590/1982-0224-20170033>.
- Magalhães, A.L.B.; Brito, M.F.G.; Sarrouh, B., 2019. An inconvenient routine: introduction, establishment and spread of new non-native fishes in the Paraíba do Sul River basin, Minas Gerais, Brazil. *Neotropical Biology and Conservation*, v. 14 (3), 329-338. <https://doi.org/10.3897/neotropical.14.e38058>.
- Marques, A.C.P.B.; Franco, A.C.S.; Salgueiro, F.; García-Berthou, E.; Santos, L.N., 2016. Genetic divergence among invasive and native populations of the yellow peacock cichlid *Cichla kelberi*. *Journal of Fish Biology*, v. 89, 2595-2606. <https://doi.org/10.1111/jfb.13144>.
- Mezzaroba, L.; Debona, T.; Frota, A.; Graça, W.J.; Gubiani, É.A., 2021. From the headwaters to the Iguassu Falls: inventory of the ichthyofauna in the Iguassu River basin shows increasing percentages of non-native species. *Biota Neotropica*, v. 21, e20201083. <https://doi.org/10.1590/1676-0611-BN-2020-1083>.
- Mineropar, 2010. Parque Nacional do Iguaçu. <http://www.mineropar.pr.gov.br/modules/conteudo/conteudo.php?conteudo=12>.
- Mulhollem, J.J.; Colombo, R.E.; Wahl, D.H., 2016. Effects of heated effluent on Midwestern US lakes: implications for future climate change. *Aquatic Sciences*, v. 78, 743-753. <https://doi.org/10.1007/s00027-016-0466-3>.
- Naimi, B.; Hamm, N.A.S.; Groen, T.A.; Skidmore, A.K.; Toxopeus, A.G., 2014. Where is positional uncertainty a problem for species distribution modelling? *Ecography*, v. 37, 191-203. <https://doi.org/10.1111/j.1600-0587.2013.00205.x>.

- Neves, M.P.; Delariva, R.L.; Guimarães, A.T.B.; Sanches, P.V., 2015. Carnivory during ontogeny of *Plagioscion squamosissimus*: a successful non-native fish in a lentic environment of the upper Paraná River basin. *PLoS One*, v. 10, e0141651. <https://doi.org/10.1371/journal.pone.0141651>
- Nimet, J.; Guimarães, A.T.B.; Delariva, R.L., 2017. Use of muscular cholinesterase of *Astyanax bifasciatus* as a biomarker in biomonitoring of rural streams. *Bulletin of Environmental Contamination and Toxicology*, v. 99, 232-238. <https://doi.org/10.1007/s00128-017-2111-9>.
- Orlandi-Neto, A.; Caneppele, D.; Marques, H.; Dias, J.H.P.; Balbuena, J.A. et al., 2024. Long-term impact of an invasive predator on the diversity of fish assemblages in a Neotropical reservoir. *Biological Invasions*, v. 26 (4), 1255-1267. <https://doi.org/10.1007/s10530-023-03243-9>.
- Pavanelli, C.S.; Graça, W.J.; Zawadzki, C.H.; Suzuki, H.I.; Fugü, R. et al., 2023. Peixes comerciais do reservatório de Itaipu. EDUEM, Maringá.
- Peat, T.B.; Gutowsky, L.F.G.; Doka, S.E.; Midwood, J.D.; Lapointe, N.W.R. et al., 2016. Comparative thermal biology and depth distribution of large-mouth bass (*Micropterus salmoides*) and northern pike (*Esox lucius*) in an urban harbour of the Laurentian Great Lakes. *Canadian Journal of Zoology*, v. 94, 767-776. <https://doi.org/10.1139/cjz-2016-0053>.
- Pelice, F.M.; Latini, J.D.; Agostinho, A.A., 2015. Fish fauna disassembly after the introduction of a voracious predator: main drivers and the role of the invader's demography. *Hydrobiologia*, v. 746 (1), 271-283. <https://doi.org/10.1007/s10750-014-1911-8>.
- Pelice, F.M.; Agostinho, A.A.; Alves, C.B.M.; Arcifa, M.S.; Azevedo-Santos, V.M. et al., 2023. Unintended consequences of valuing the contributions of non-native species: misguided conservation initiatives in a megadiverse region. *Biodiversity and Conservation*, v. 32 (12), 3915-3938. <https://doi.org/10.1007/s10531-023-02666-z>.
- Pereira, F.W.; Vitule, J.R.S., 2019. The largemouth bass *Micropterus salmoides*: impacts of a powerful freshwater fish predator outside of its native range. *Reviews in Fish Biology and Fisheries*, v. 29, 639-652. <https://doi.org/10.1007/s11160-019-09570-2>.
- Phillips, S.J.; Anderson, R.P.; Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, v. 190 (3-4), 231-259. <https://doi.org/10.1016/j.ecolmodel.2005.03.026>.
- Phillips, S.J.; Anderson, R.P.; Dudík, M.; Schapire, R.E.; Blair, M.E., 2017. Opening the black box: an open-source release of Maxent. *Ecography*, v. 40, 887-893. <https://doi.org/10.1111/ecog.03049>.
- Queiroz-Sousa, J.; Brambilla, E.M.; Garcia-Ayala, J.R.; Travassos, F.A.; Daga, V.S. et al., 2018. Biology, ecology and biogeography of the South American silver croaker. *Reviews in Fish Biology and Fisheries*, v. 28, 693-714. <https://doi.org/10.1007/s11160-018-9526-1>.
- R Core Team, 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org/>.
- Rahel, F.J.; Olden, J.D., 2008. Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, v. 22 (3), 521-533. <https://doi.org/10.1111/j.1523-1739.2008.00950.x>.
- Rauber, R.G.; Oliveira, A.G.; Lopes, T.M.; Dias, R.M.; Alves, D.C. et al., 2024. Changes in fish functional diversity in a Neotropical floodplain associated with the invasive *Cichla* spp.: a long-term perspective. *Hydrobiologia*, 1-14. <https://doi.org/10.1007/s10750-024-05725-w>.
- Ruaro, R.; Conceição, E.O.; Silva, J.C.; Cafofo, E.G.; Angulo-Valencia, M.A. et al., 2019. Climate change will decrease the range of a keystone fish species in La Plata River Basin, South America. *Hydrobiologia*, v. 836, 1-19. <https://doi.org/10.1007/s10750-019-3904-0>.
- Seebens, H.; Bacher, S.; Blackburn, T.M.; Capinha, C.; Dawson, W. et al., 2021. Projecting the continental accumulation of alien species through to 2050. *Global Change Biology*, v. 27 (5), 970-982. <https://doi.org/10.1111/gcb.15333>.
- Seebens, H.; Meyerson, L.A.; Richardson, D.M.; Lenzner, B.; Tricarico, E. et al., 2025. Biological invasions: a global assessment of geographic distributions, long-term trends and data gaps. *Biological Reviews*, v. 100 (6), 2542-2583. <https://doi.org/10.1111/brv.70058>.
- Sharma, S.D.A.; Jackson, D.A.; Minns, C.K., 2007. Will northern fish populations be in hot water because of climate change? *Global Change Biology*, v. 13, 2052-2064. <https://doi.org/10.1111/j.1365-2486.2007.01426.x>.
- Simberloff, D.; Rejmánek, M. (Eds.), 2011. Encyclopedia of biological invasions. University of California Press, Berkeley.
- Spairani, M.; Boz, B.; Papatheodoulou, A.; Polazzo, A.; Tziortzis, I. et al., 2025. Distribution and population structure of introduced rainbow trout *Oncorhynchus mykiss* in Cyprus. *Aquatic Ecology*, 1-11. <https://doi.org/10.1007/s10452-025-10173-2>.
- Sunny, A.; Ruiz-Reyes, J.; Domínguez-Vega, H.; Gómez-Ortiz, Y.; Heredia-Bobadilla, R.L. et al., 2024. Niche overlap by invasion of *Oncorhynchus mykiss* on the habitat of its amphibian prey in central Mexico. *Biological Invasions*, v. 26 (7), 2183-2201. <https://doi.org/10.1007/s10530-024-03304-7>.
- Tonella, L.H.; Fugü, R.; Vitorino, O.B.; Suzuki, H.I.; Gomes, L.C. et al., 2018. Importance of feeding strategies on the long-term success of fish invasions. *Hydrobiologia*, v. 817, 239-252. <https://doi.org/10.1007/s10750-017-3404-z>.
- Tonella, L.H.; Ruaro, R.; Daga, V.S.; Garcia, D.A.Z.; Vitorino, O.B. et al., 2023. Neotropical freshwater fishes: A Dataset of Occurrence and Abundance of Freshwater Fishes in the Neotropics. *Ecology*, v. 104 (4), e3713. <https://doi.org/10.1002/ecy.3713>.
- Vitule, J.R.S., 2009. Introdução de peixes em ecossistemas continentais brasileiros: revisão, comentários e sugestões de ações contra o inimigo quase invisível. *Neotropical Biology and Conservation*, v. 4 (2), 111-122.
- Vitule, J.R.S.; Bornatowski, H.; Freire, C.A.; Abilhoa, V., 2014. Extralimital introductions of *Salminus brasiliensis* for sport fishing purposes: a growing challenge for the conservation of biodiversity in Neotropical aquatic ecosystems. *BioInvasions Records*, v. 3 (4), 291-296. <https://doi.org/10.3391/bir.2014.3.4.11>.
- Vitule, J.R.S.; Occhi, T.V.; Kang, B.; Matsuzaki, S.I.; Bezerra, L.A. et al., 2019. Intra-country introductions unraveling global hotspots of alien fish species. *Biodiversity and Conservation*, v. 28, 3037-3043. <https://doi.org/10.1007/s10531-019-01815-7>.
- Yoğurtcuoğlu, B.; Bucak, T.; Ekmekçi, F.G.; Kaya, C.; Tarkan, A.S., 2021. Mapping the establishment and invasiveness potential of rainbow trout (*Oncorhynchus mykiss*) in Turkey. *Frontiers in Ecology and Evolution*, v. 8, 599881. <https://doi.org/10.3389/fevo.2020.599881>.